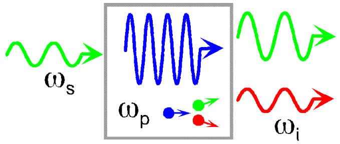
NASA-DoD Workshop on Quantum Imaging and Metrology
Pasadena, CA, November 14–15, 2002



Spatially Broadband Parametric Amplification: Quantum-Noise Correlations and Noiseless Amplification of Images

Prem Kumar

Center for Photonic Communication and Computing
ECE Department, Northwestern University, Evanston, IL 60208-3118
Tel: (847) 491-4128; Fax: (847) 467-5319; E-mail: kumarp@northwestern.edu

Outline:

- Quantum-limited sensitivity of imaging
- Parametric image amplification
- Spatial bandwidth of parametric amplification
- Quantum-noise correlations in image amplification
- Noiseless image amplification
- Potential for applications

Collaborators:

- Sang-Kyung Choi
- Michael Vasilyev
- Michael L. Marable

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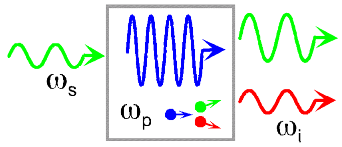
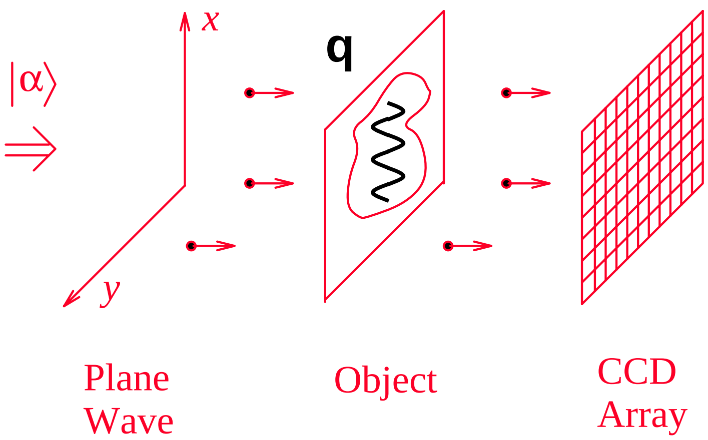
- Office of Naval Research

Applications of Quantum OPAs: Quantum-Limited Sensitivity of Imaging

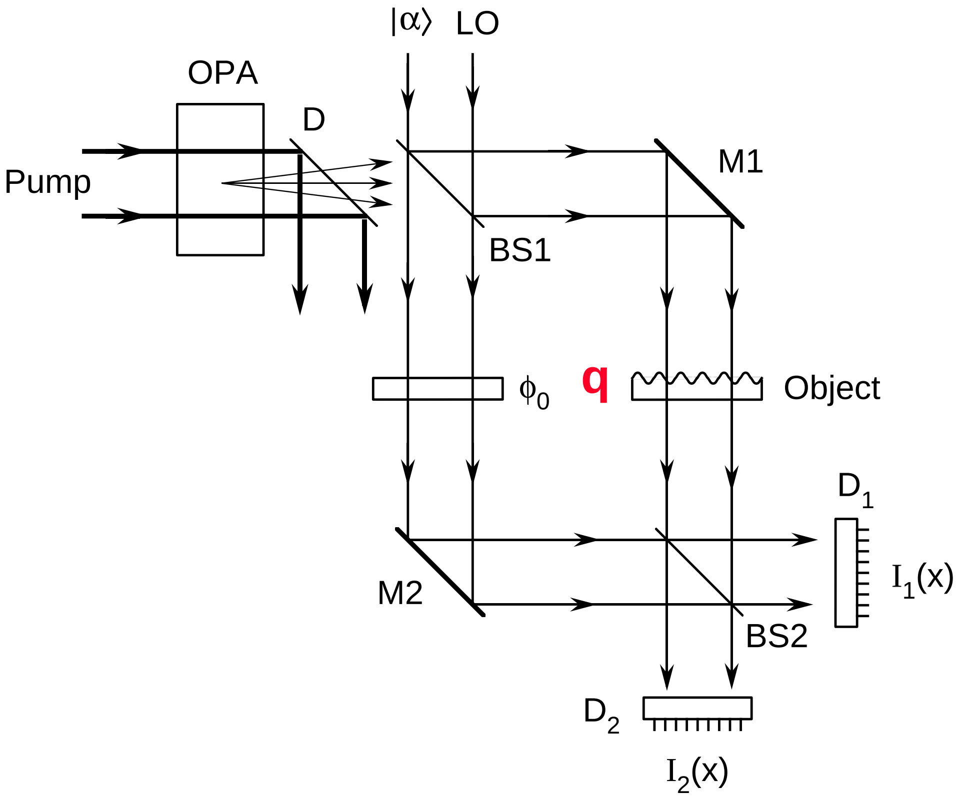


Amplitude Objects:



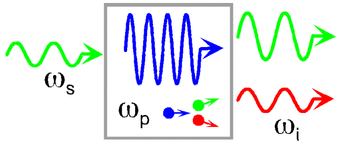
Spatially white shot noise $\propto \frac{1}{|\alpha|^2}$

Phase Objects:



- M. I. Kolobov and P. Kumar, "Sub-shot–noise microscopy: Imaging of faint phase objects with squeezed light," Opt. Lett. **18**, 849 (1993).
- P. Kumar and M. I. Kolobov, "Four-Wave Mixing as a Source for spatially broadband squeezed light," Opt. Commun. **104**, 374 (1994).

Amplification & Imaging



Noiseless amplification:

- coherent light $\xrightarrow[\text{phase-sensitive amplifier (PSA)}]{\text{parametric downconversion}}$ light with **amplified amplitude** / *squeezed phase*
- noise performance of PSA is better than quantum limit of phase-insensitive amplifier (PIA) (Kimble, 1993; Levenson, 1993)

Parametric imaging:

- parametric up-conversion of infrared images (Midwinter, 1968; Firester, 1969; Andrews, 1970)
- parametric amplification of images (Fainman, 1986; Laferriere, 1989; Devaux, 1995)

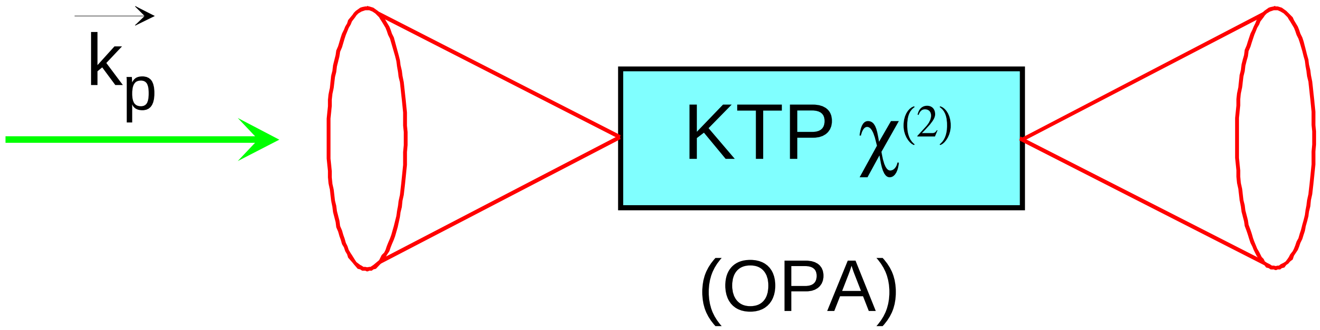
Motivation:

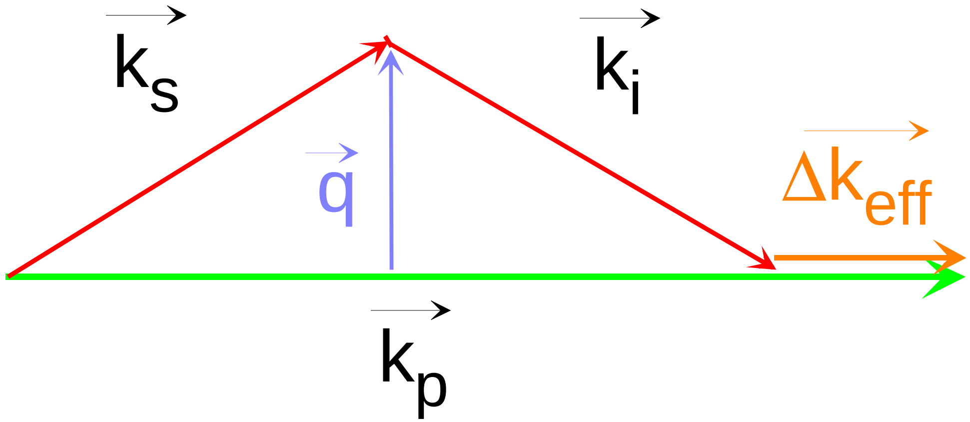
- Utilize phase-sensitive optical parametric amplifier (OPA) to improve imaging
  better amplifier noise figure (NF) $\longrightarrow$ better detection sensitivity

Potential applications:

- Enhancement of time-gated image recovery
  (Faris, 1994; Brun, 1995; Cameron, 1996; Lantz, 1997)
- Enhancement of faint images

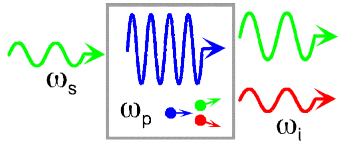
Spatially Broadband OPA & Phase Matching

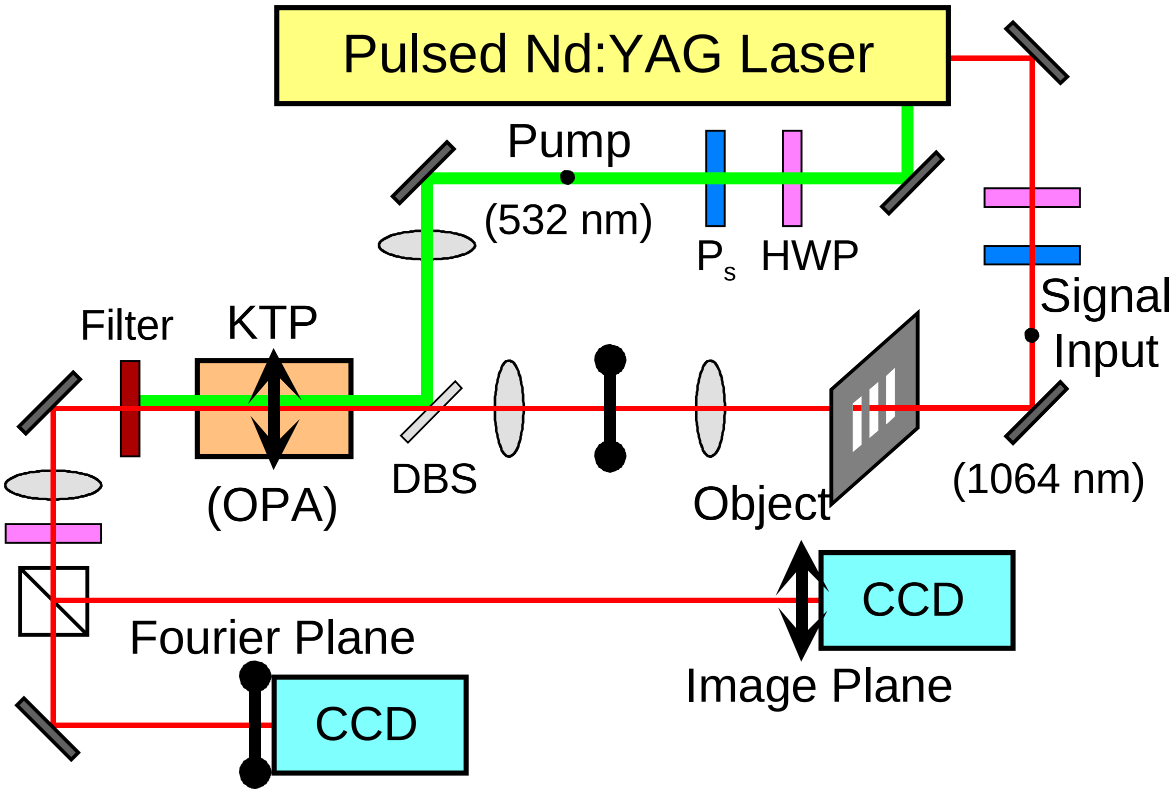




$\Delta k_{eff} \cong 0$ for $q < q_{max} \approx (k_p / \text{length})^{1/2}$

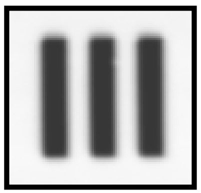
Setup for Parametric Image Amplification





16 lines/mm

Object Plane



bare signal | amplified signal | idler

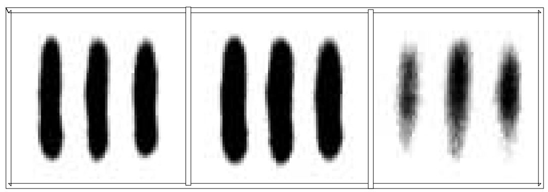


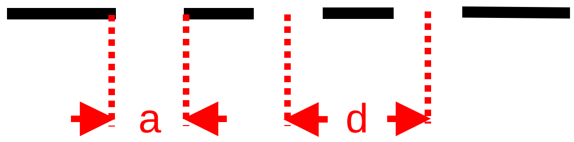
Image Plane

3-Slit Object for Imaging

16 lines/mm

d = 2 a = 62.5 μm

Element 4.1



Fourier transform of 3 slits:

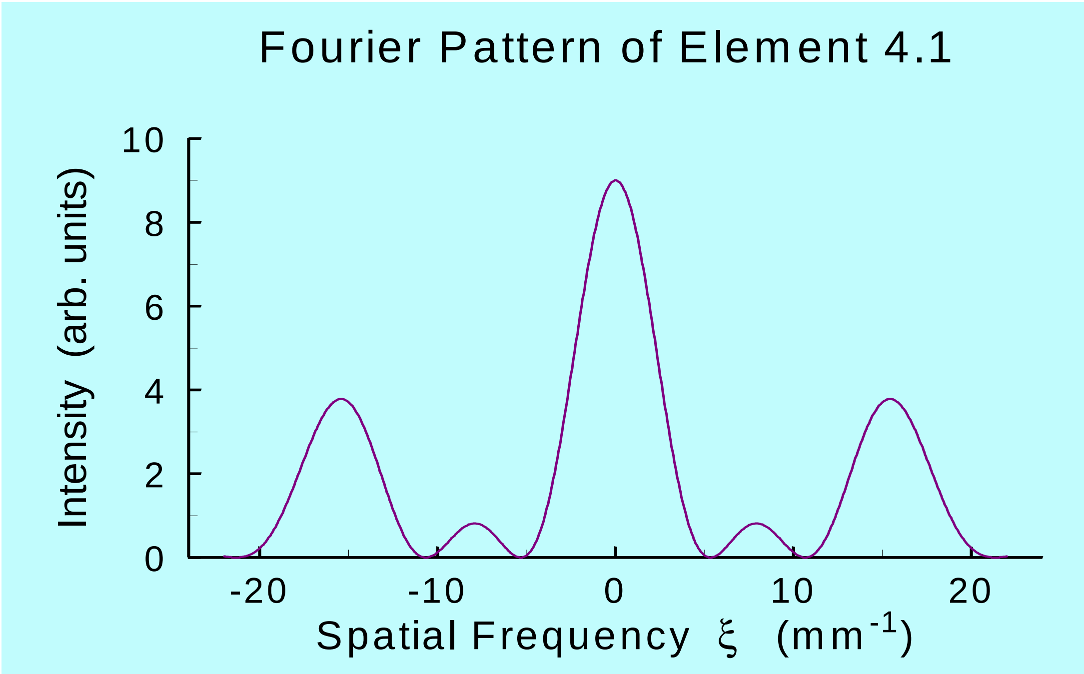
$$I = I_0 \left(\frac{\sin\alpha}{\alpha}\right)^2 \left(\frac{\sin 3\beta}{\sin\beta}\right)^2$$

$$\alpha = 0.5\, k\, a \sin\theta$$

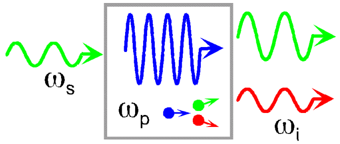
$$\beta = 0.5\, k\, d \sin\theta$$

$$q = 2\pi\xi$$

$$\longrightarrow \quad I(\xi) = I_0 \left(\frac{\sin \pi a\xi}{\pi a\xi}\right)^2 \left(\frac{\sin 3\pi d\xi}{\sin \pi d\xi}\right)^2$$



Parametrically Amplified Images



Object Plane

16 lines/mm

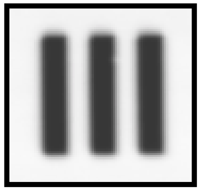
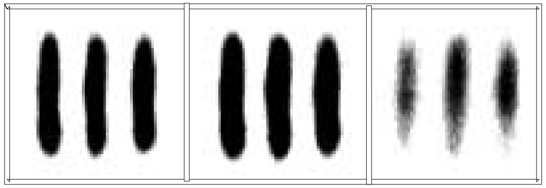


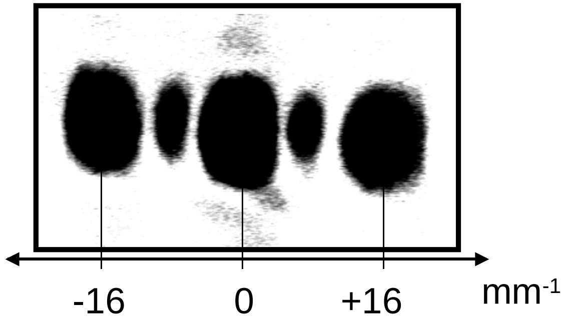
Image Plane

bare signal | amplified signal | idler

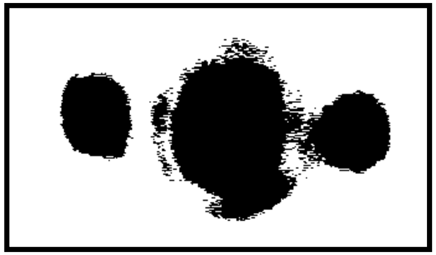


Fourier Plane

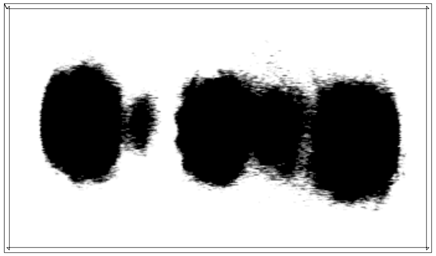
Bare Signal



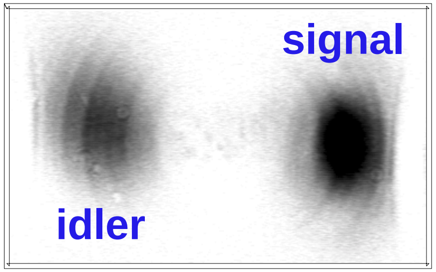
Amplified Signal (Low-Pass OPA)



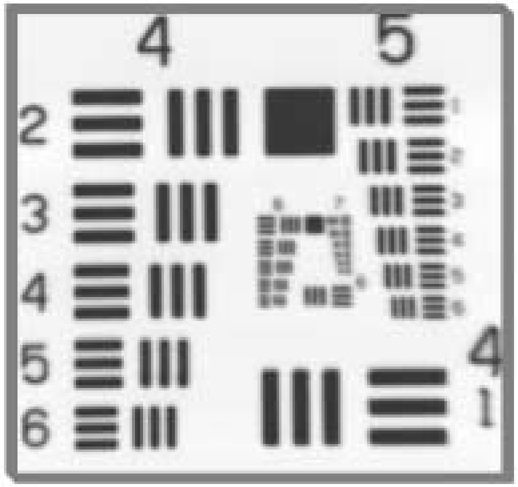
Amplified Signal (Band-Pass OPA)



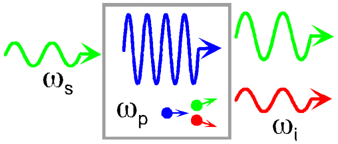
Correlated Twin Beams



USAF Test Pattern



Setup for Noise Measurements

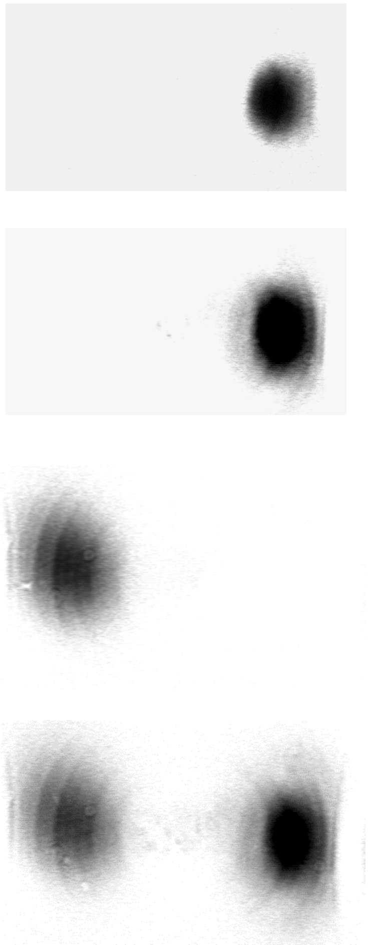


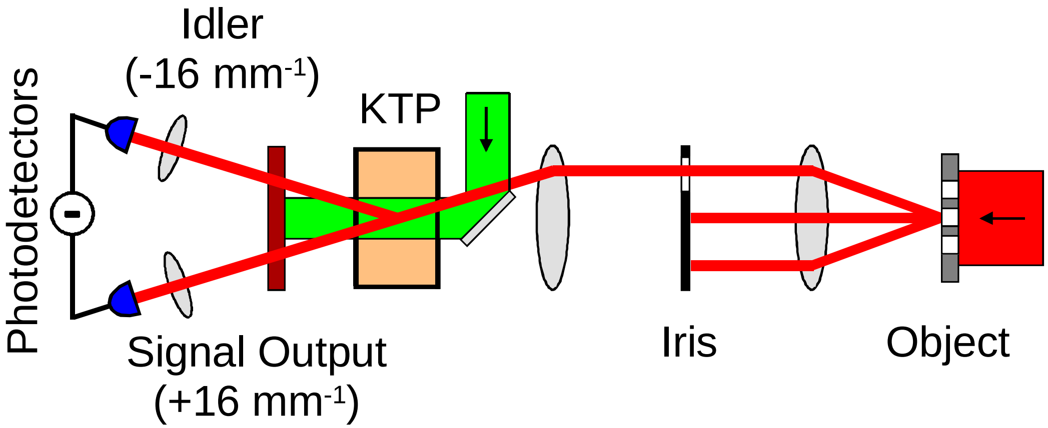
Input Signal

Amplified Signal

Idler

Amplified Signal / Idler

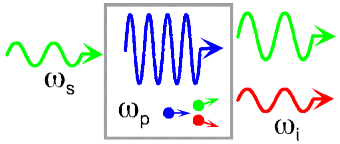




Top View of the Layout

[Images for Noise Measurements]

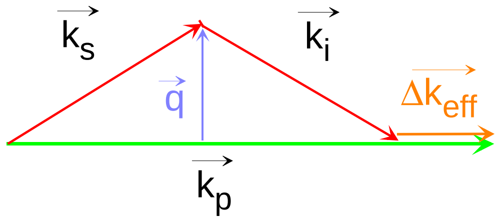
Spatially Broadband OPA Theory



Parametric gain: phase-insensitive gain $G_{PIA} = |\mu|^2$

phase-sensitive gain $G_{PSA} = 2G_{PIA} - 1 + 2\sqrt{G_{PIA}(G_{PIA} - 1)}$

Twin beam noise reduction: $R = \dfrac{\eta}{|\mu|^2 + |\nu|^2} + 1 - \eta$



$$\mu = [\cosh(hl) + \frac{i\Delta k_{eff}}{2h}\sinh(hl)]\exp(-\frac{i\Delta k_{eff} l}{2})$$

η = quantum efficiency

$$\nu = -\frac{ig}{2h}\sinh(hl)\exp(-\frac{i\Delta k_{eff} l}{2})$$

$$h = \frac{1}{2}\sqrt{|g|^2 - \Delta k_{eff}^{\ 2}}$$

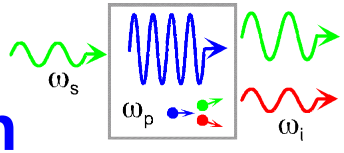
$g \propto$ (pump intensity)$^{1/2}$

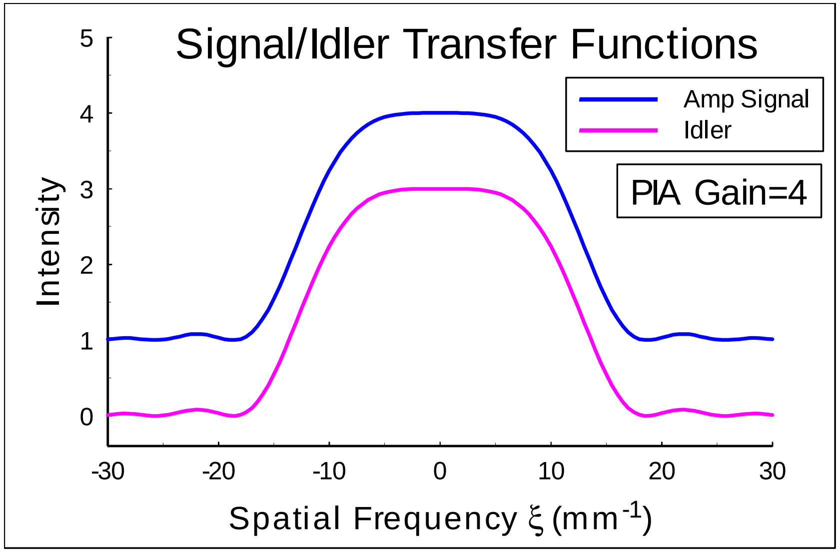
$$\Delta k_{eff} = k_p - k_s - k_i + \frac{q^2}{2}(\frac{1}{k_s} + \frac{1}{k_i})$$

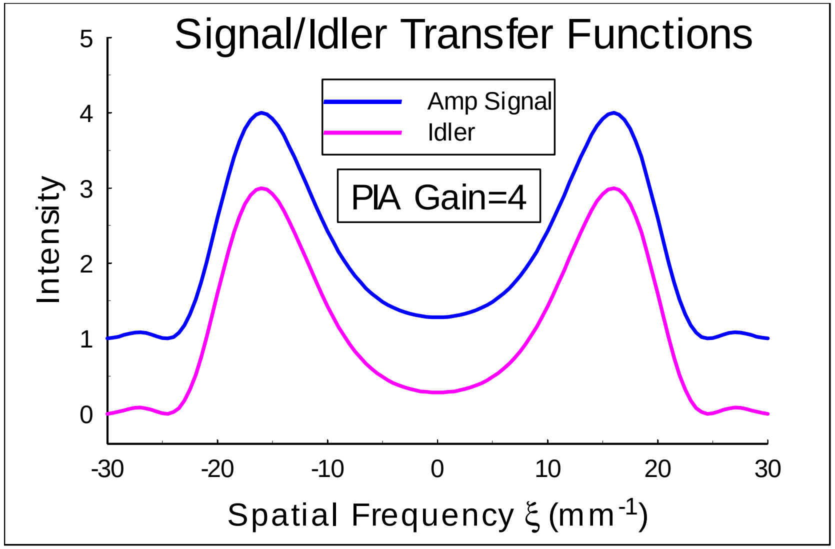
l = length of nonlinear crystal

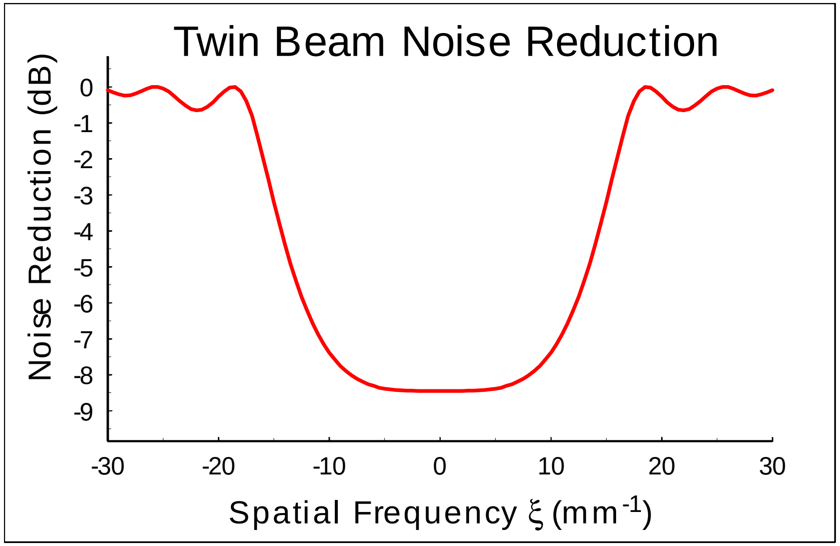
ref.: A. Gavrielides, P. Peterson, and D. Cardimona,
J. Appl. Phys. **62**, 2640 (1987).

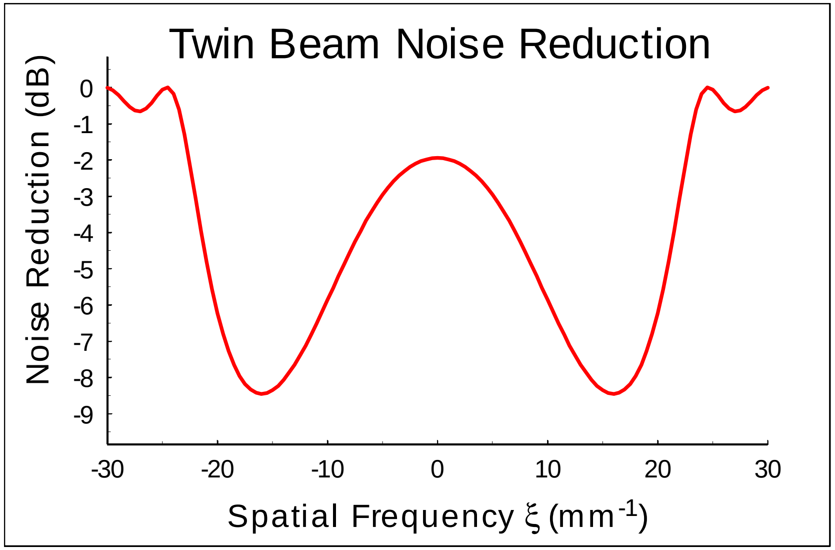
Spatially-Broadband OPA:
Spatial Spectra of Gain and Noise Reduction





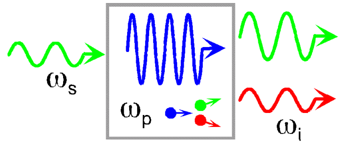






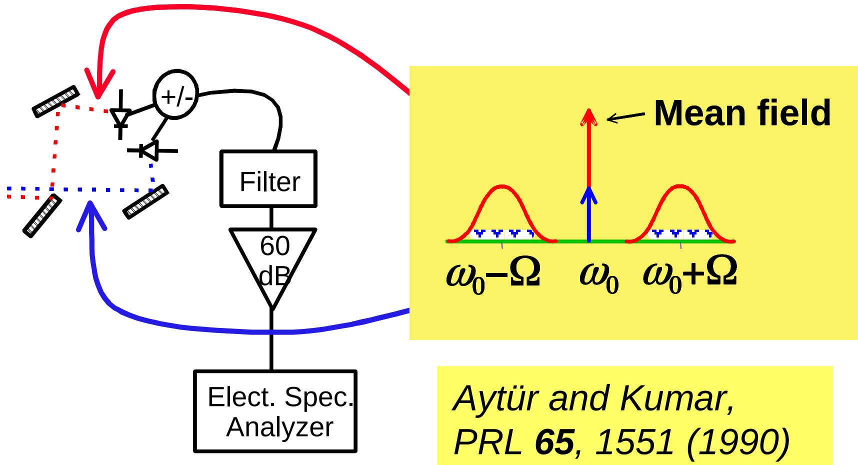
Low-Pass Configuration

Band-Pass Configuration



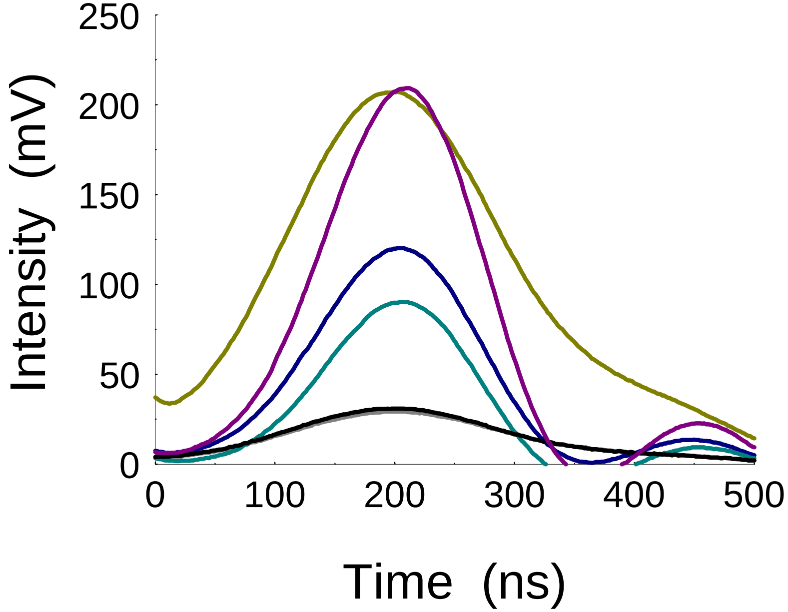
Temporal Pulse Profiles

- bare
- signal
- idler
- sum
- difference
- coherent

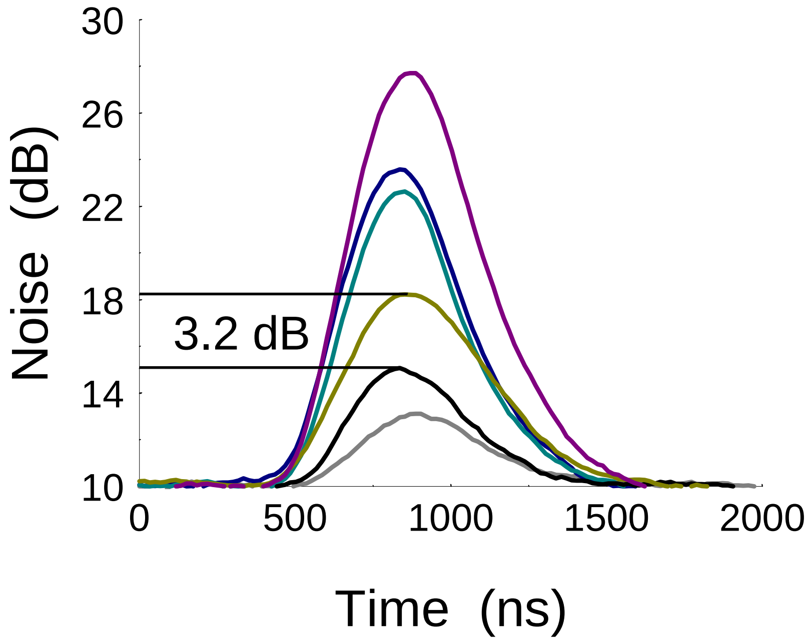


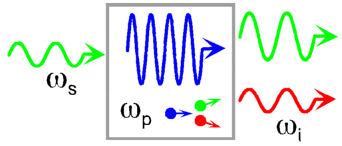
*Aytür and Kumar, PRL **65**, 1551 (1990)*

Mean Field Intensities

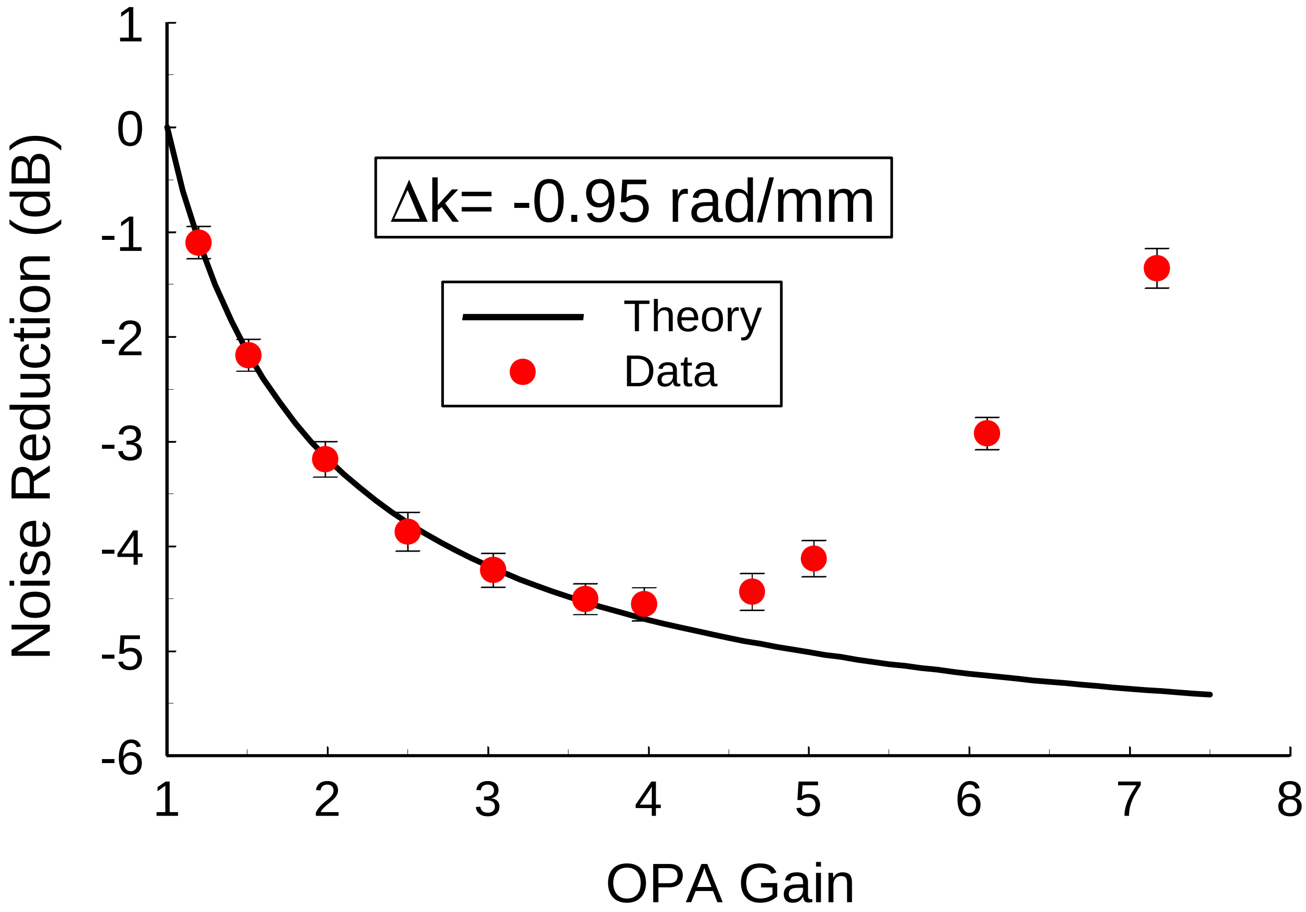


Noise Power



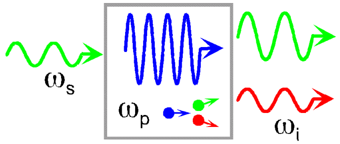


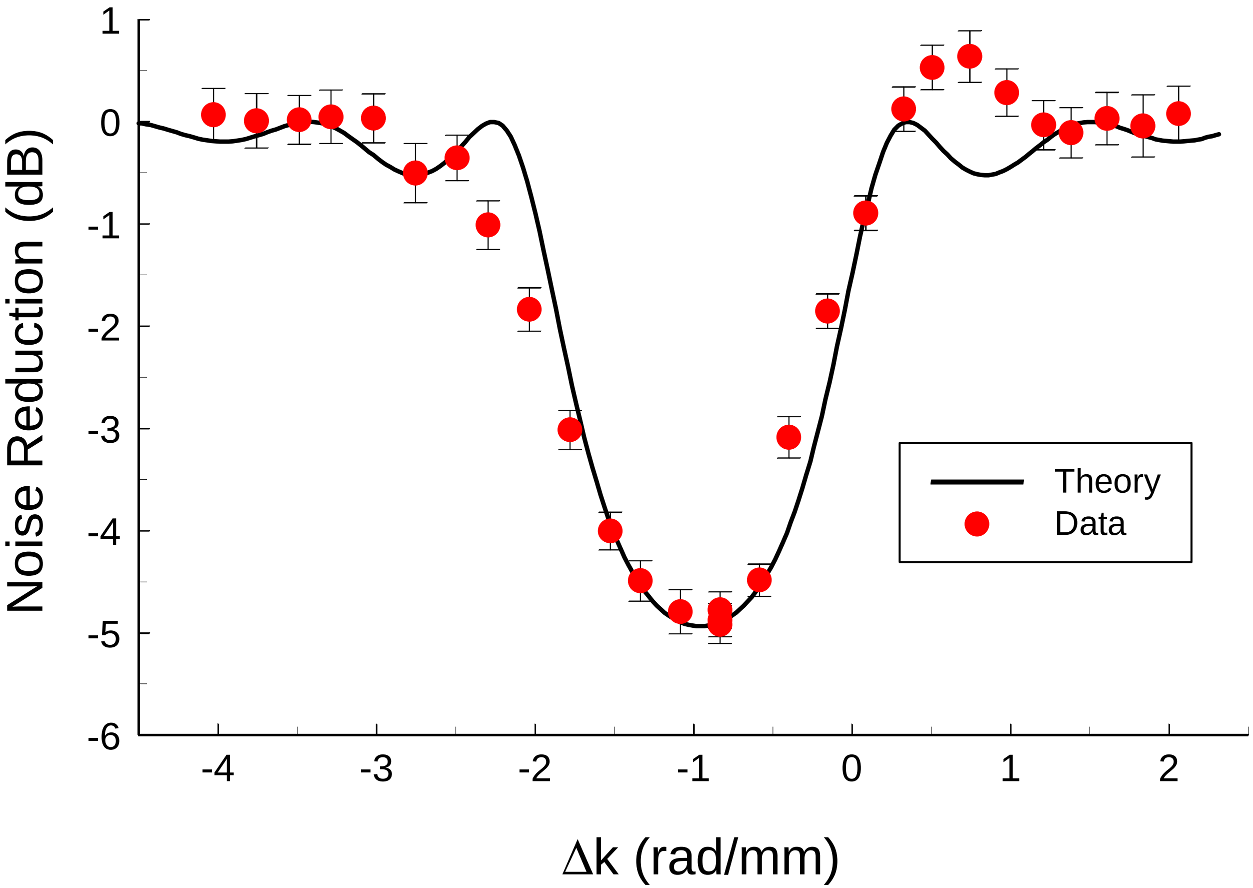
Twin-Beam Noise Reduction vs. OPA Gain



M. L. Marable, S-K. Choi, and P. Kumar, *Optics Express* **2**, 84–92 (1998).

Twin-Beam Noise Reduction vs. Δk





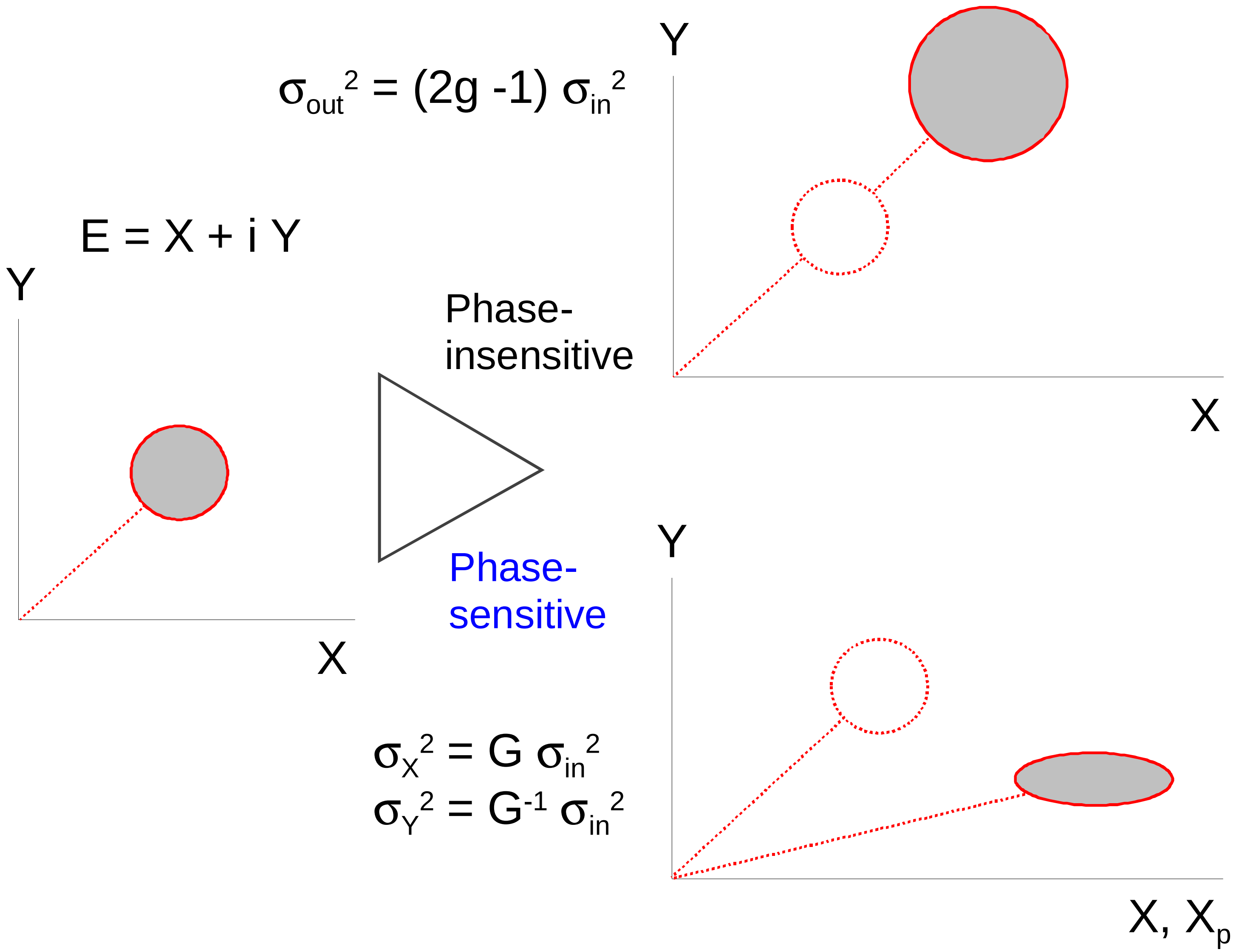
M. L. Marable, S-K. Choi, and P. Kumar, *Optics Express* **2**, 84–92 (1998).

Amplification of Coherent Light Input

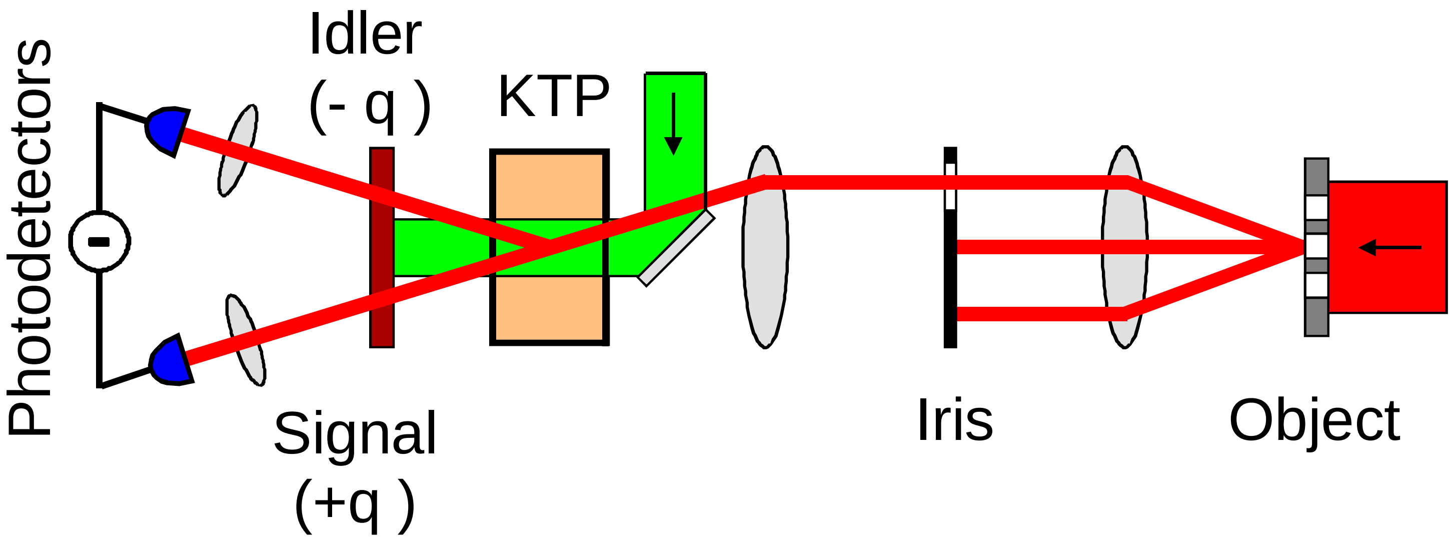
$$E = X + i\,Y$$

$$\sigma_{out}^2 = (2g - 1)\,\sigma_{in}^2$$

$$\sigma_X^2 = G\,\sigma_{in}^2$$
$$\sigma_Y^2 = G^{-1}\,\sigma_{in}^2$$



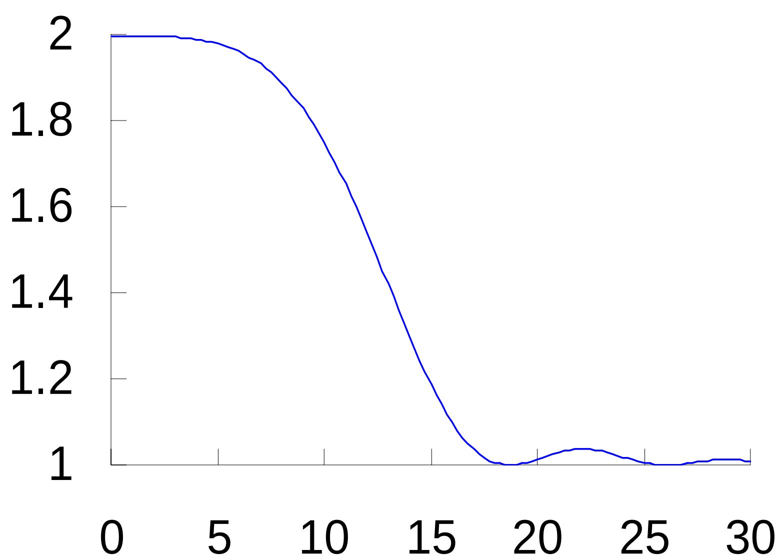
Measurement of Spatial Bandwidth of OPA



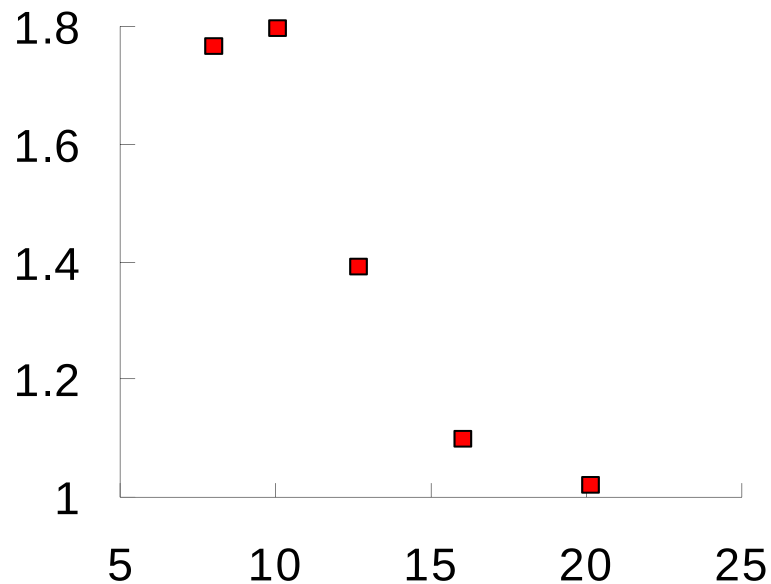
- Layout for noncollinear twin beam noise reduction measurement
- Spatial bandwidth found by measuring G_q of signal at fixed G_0 for objects of various resolution

Measurement of Spatial Bandwidth of OPA

Theory



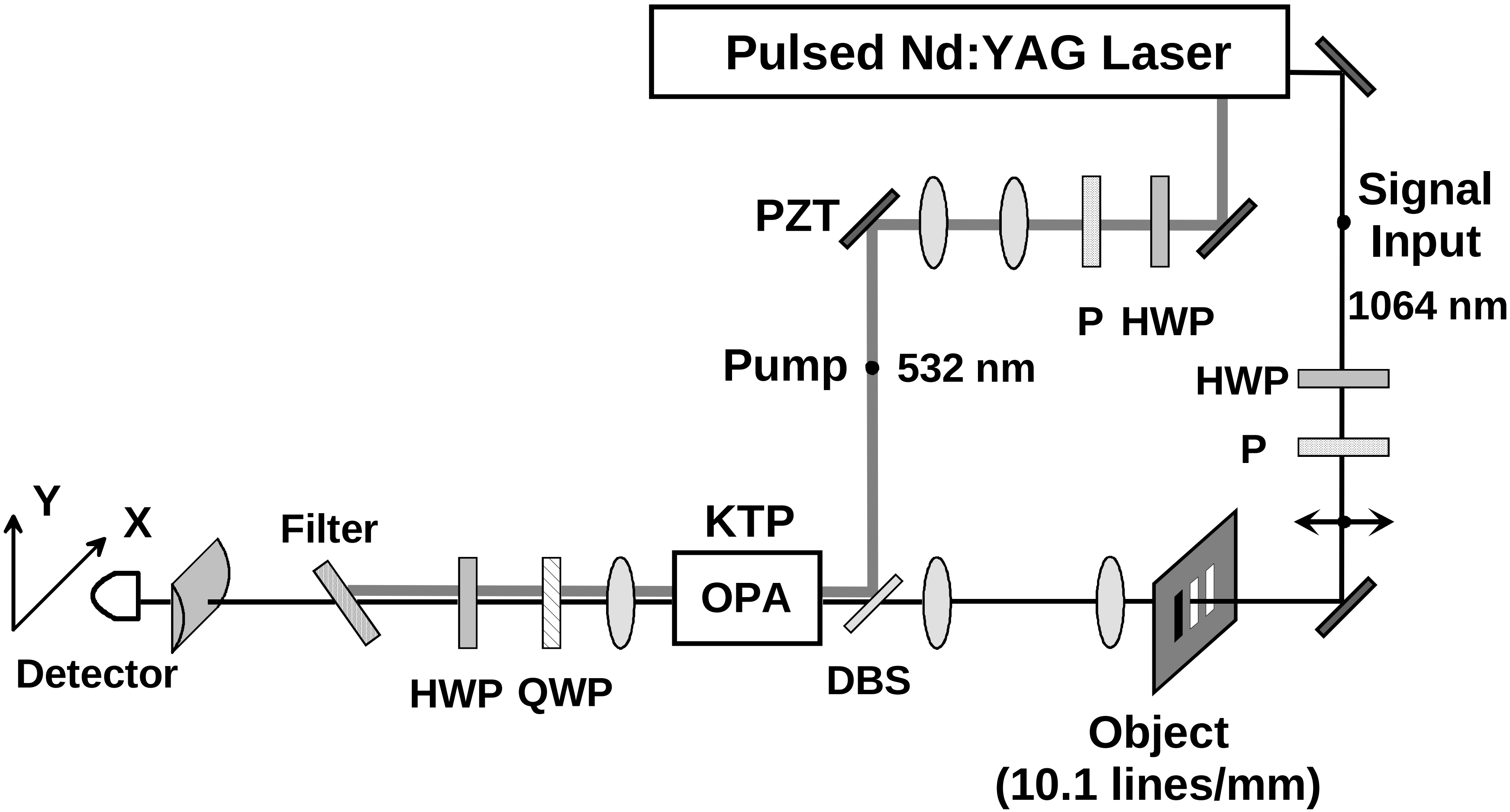
Measured G_q



- Spatial transfer function, that is, amplified signal vs. spatial frequency
- $G_0 = 2$ in 5 mm KTP crystal

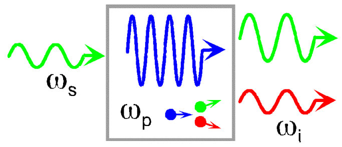
- Gain at various spatial frequencies with fixed gain for 0th component
- $G_0 = 2$ in 5 mm KTP crystal

Layout for Noiseless Image Amplification

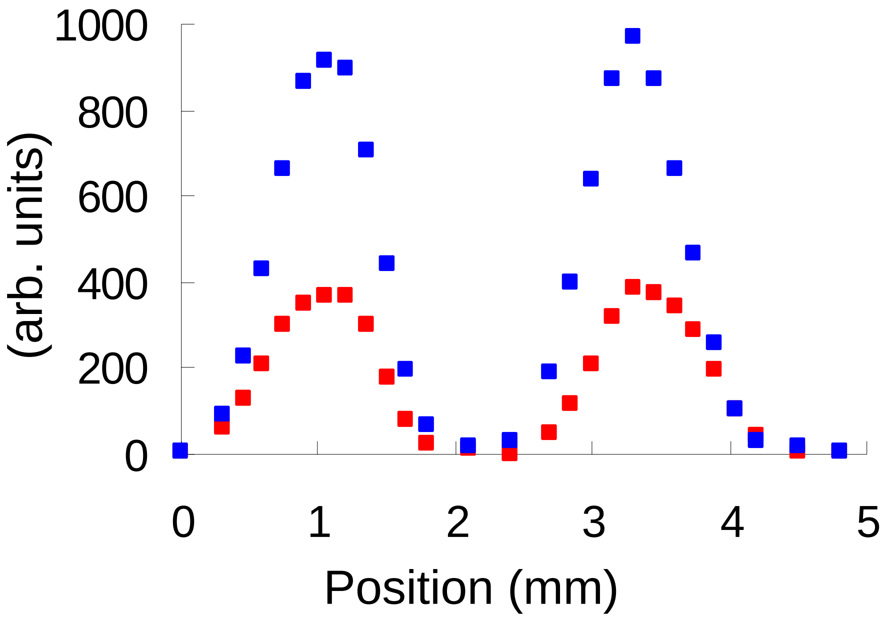


S.-K. Choi, M. Vasilyev, and P. Kumar, *Phys. Rev. Lett.* **83**, 1938 –1941 (1999).

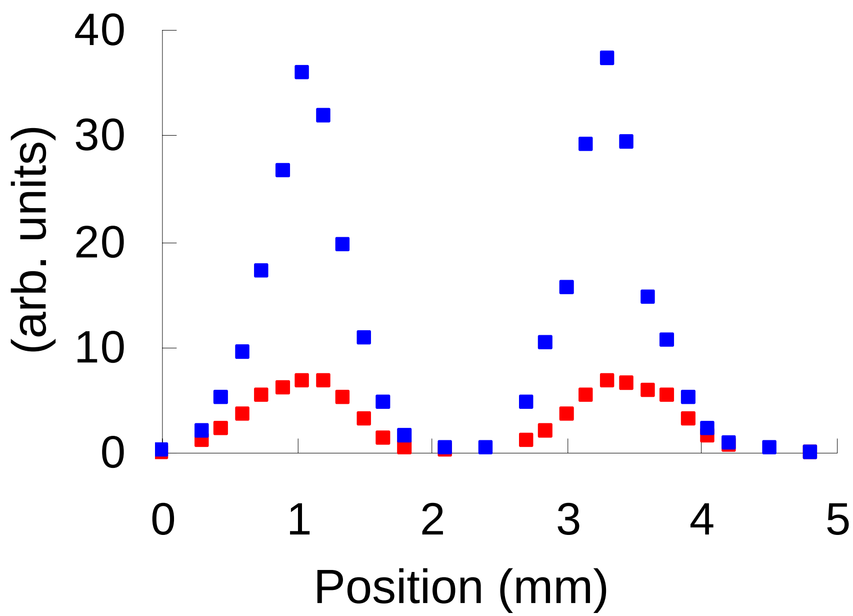
Spatial Profiles of 1-d Image



Intensity Profile

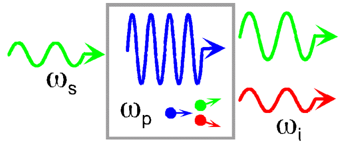


Noise Power Profile



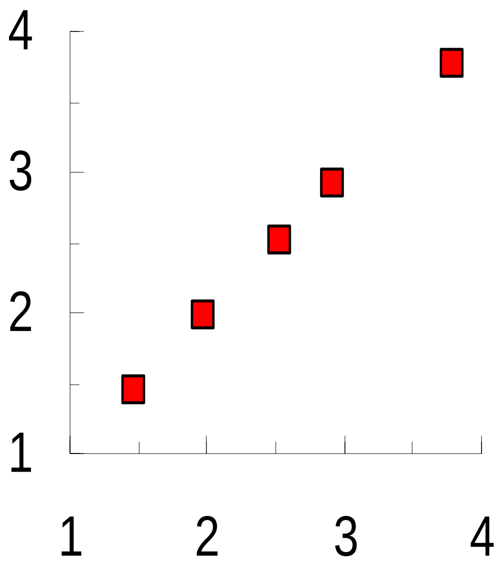
- 2-slit object magnified x24 and then compressed in one dimension
- Spatial profiles scanned by photodetector in horizontal direction
- Red squares – bare profile; Blue squares – PSA profile
- 3.25 mm KTP crystal

S.-K. Choi, M. Vasilyev, and P. Kumar, *Phys. Rev. Lett.* **83**, 1938 –1941 (1999).



Amplifier Noise Figure

DC gain vs. 27 MHz gain



- Experimental $NF_{amp+loss}$

$$= \frac{1}{\eta}\ \frac{(27\text{ MHz gain})}{(\text{DC gain })^2}$$

- $NF_{amp+loss} = NF_{amp} + (1-\eta)/(\eta G)$

- PIA $SNR_{out} = \dfrac{\eta G}{2\eta G + 1 - 2\eta} SNR_{in}$

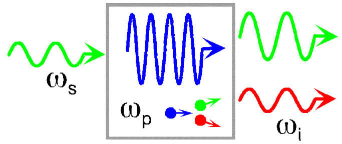
$$NF_{amp+loss} = 2 + \frac{1}{\eta G} - \frac{2}{G}$$

- PSA $SNR_{out} = \dfrac{\eta G}{\eta G + 1 - \eta} SNR_{in}$

$$NF_{amp+loss} = 1 + \frac{1-\eta}{\eta G}$$

PSA gain G = 2.5-2.6 Quantum eff. η = 0.82

$NF_{amp+loss}$	3.25mm KTP	5.21mm KTP
PSA Exp. @ peaks	1.05 $\pm$ 0.1 0.2 $\pm$ 0.6 dB	1.10 $\pm$ 0.1 0.4 $\pm$ 0.5 dB
PSA Theory	1.1 0.4 dB	1.1 0.4 dB
PIA Theory	1.7 2.3 dB	1.7 2.3 dB



Conclusions

Quantum Noise Correlations In Image Amplification

- Observation of quantum noise reduction in non-collinear twin beams
  5 dB below the shot-noise level

- Good agreement with theory of spatially-broadband OPA

- Bandpass OPA selects spatial frequency for amplification

Noiseless Image Amplification

- Spatially broadband noiseless image amplification
  PSA gain $\cong$ 2.5 and $NF_{amp} \cong 0$ dB at peaks of amplified 2-slit image

- Improvement of detected SNR due to pre-amplification before loss
  $NF_{amp+loss} \cong 0.2\text{-}0.4$ dB $<$ $NF_{bare+loss} \cong 0.9$ dB